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The Five Volume Final Report was too large for electronic submittal, and hence was mailed directly to the Program Manager, Dr. J. Schmisseur at AFOSR/NA.

14. ABSTRACT
The objective of this project is improved understanding of the response of boundary layers to surface variations for control. The subsonic studies provide a significant advancement in our understanding of boundary layer stability to small-scale roughness, which has the potential for significant drag and heat transfer reduction across all Mach numbers. The high-speed (M=5) high Reynolds number studies provide improvedunderstanding of the response of turbulence to mechanical non-equilibrium, which led to a flow control strategy, where 25% reductions in turbulence levels were demonstrated. Our modeling suggests this could lead to a 40% reduction in surface heat transfer.

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Mechanisms for Control of Boundary-Layer Turbulence across the Speed Regimes

AFOSR GRANT FA9550-08-1-0093

SECTION 1

Summary Information

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EXECUTIVE SUMMARY

Research Objectives

The overarching objective of this project was to improve the basic understanding of the response of turbulence to surface variations and to use this information to develop localized control strategies. In the proposal, the research was divided into two basic steps. The first was fundamental studies to verify and model the basic mechanisms for control. The second was to exploit the mechanisms for active control. The proposed research effort was to focus primarily on subsonic, $U_\infty = 5$ to 30 m/s (Klebanoff-Saric Low Disturbance Tunnel), and supersonic, $M =$ 3.0 to 5.0 (NAL High Reynolds Number Wind Tunnel), flows. Theoretical modeling and control were to focus on these speeds, and most experiments were to be performed in these regimes. The primary emphasis at the high-Mach condition was passive cooling or aero-optic distortion reduction.

Status of the Effort

In terms of contributions, the subsonic studies provide a significant advancement in our understanding of boundary layer stability and control via small-scale roughness, which has the potential for significant drag and heat transfer reduction across all Mach numbers. The high-speed (M=5) high Reynolds number studies provide improved understanding of the response of turbulence to mechanical non-equilibrium, which led to a passive flow control strategy that resulted in 25% reductions in turbulence levels. Our modeling suggests this could lead to a 40% reduction in localized surface heat transfer.

Final Report

The Final Report for AFOSR Grant FA9550-08-1-0093 is divided into five Sections. Provided in Section 1 (this section) are the project summary information. Presented in Sections 2 – 5 are the project results. These Sections exceeded the allowable size for electronic submittal. Hence, they were mailed directly to the Program Manager, Dr. John Schmisseur (AFOSR/NA). Abstracts from each Section are summarized in the remainder of this Section.

SECTION 2

Mechanisms for Boundary Layer Turbulence Control at Mach 5.0

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Abstract

The research objectives for the Mach 5.0 studies were to extend our understanding, and modeling, of the turbulence response to global and local mechanical non-equilibrium effects, and then use this knowledge to demonstrate localized control of boundary layer turbulence using small, $O(1/10^{\text{th}})$ of the boundary layer thickness, surface elements.

The first goal for this project was to assess the performance of existing turbulence models to capture the salient trends on the turbulence response to global and local mechanical non-equilibrium. This was accomplished via a thorough assessment of our Mach 3.0 database, which showed that the response of the turbulence to local pressure gradients followed the global trend. This indicated that low-order two-equation turbulence models should capture local mechanical non-equilibrium effects if the roughness elements are resolved. Detailed RANS and DES calculations were performed, which confirmed the hypothesis.

The second goal was to characterize the influence of increasing the Mach number from on the underlying processes. This was accomplished via an extensive experimental campaign to extend our mechanical non-equilibrium database to Mach 5.0. These data confirmed the trends observed earlier at Mach 3.0. Acquisition of this database represents the bulk of the high-speed study, where considerable effort was placed on refining our particle image velocimetry methods to enable measurements to within 50 viscous units of the wall. Although the data analyses were preliminary at the time of this writing, the data have proven valuable toward improving our understanding of the underlying physical mechanisms. In summary, an extensive high resolution PIV

database has been achieved (M = 3.0 and 5.0), where the present focus was on Mach 5.

The third goal was to numerically design and experimentally test the ability of small wall elements to control (lower) the turbulence levels in a Mach 5.0 high Reynolds number boundary layer. This goal was accomplished. Through our simulations, we predicted a peak reduction of 20%. Experimentally, we observed 25% peak reductions. A 40% reduction in the transverse turbulent stress component was observed, and our modeling suggests this could translate into a 40% reduction in the wall heat transfer.

To further advance this concept, it is recommended that (1) further study of the Mach 3 and 5 database, focused on quantification of the evolution of the structure of the turbulence (length-scales, spatial spectra and auto-correlations), be performed; (2) the isolated element control effects be verified over a wider range of flow conditions and in multiple facilities; (3) formal optimization studies be performed to properly maximize control effects; (4) surface heat transfer and optical distortion studies be conducted, and (5) studies of element activation for dynamic control should be performed.

SECTION 3

Control of Transition to Turbulence with the Study of Receptivity to 3-D Roughness Arrays on a Swept-Wing

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On-going efforts to reduce aircraft drag through transition delay focus on understanding the process of boundary-layer transition from a physics-based perspective. For swept-wings subject to transition dominated by a stationary crossflow instability, one of the remaining challenges is understanding how freestream disturbances and surface features such as surface roughness create the initial amplitudes for unstable waves. These waves grow, modify the mean flow and create conditions for secondary instabilities to occur, which in turn ultimately lead to transition. Computational methods that model the primary and secondary instability growth can accurately model disturbance evolution as long as appropriate initial conditions are supplied. Additionally, transition delay using discrete roughness arrays that exploit known sensitivities to surface roughness has been demonstrated in flight and wind tunnel testing; however, inconsistencies in performance from the two test platforms indicate further testing is required. This study uses detailed hotwire boundary-layer velocity scans to quantify the relationship between roughness height and initial disturbance amplitude. Naphthalene flow visualization provides insight into how transition changes as a result of roughness height and spacing.

Micron-sized, circular roughness elements were applied near the leading edge of the ASU(67)-0315 model installed at an angle of attack of -2.9° in the Klebanoff-Saric Wind Tunnel. Extensive flow quality measurements show turbulence intensities less than 0.02% over the speed range of interest. A survey of multiple roughness heights for the most unstable and control wavelengths and Reynolds numbers of 2.4×10^6, 2.8×10^6 and 3.2×10^6 was completed for chord locations of 10%, 15% and 20%. When care was taken to measure in the region of linear stability, it was found that the disturbance amplitude varies almost linearly with roughness height. Naphthalene flow visualization indicates that moderate changes in already-low freestream turbulence levels can have a significant impact on transition behavior.

SECTION 4

Direct Numerical Simulation of Discrete Roughness on Swept Wing Leading Edge

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Abstract

Direct numerical simulations were carried out for an array of discrete micron-sized roughness elements, which were mounted near the leading edge of a 30 deg swept wing at a chord Reynolds number of 7.4 million. To make the simulations tractable, the geometry was scaled by the wing leading-edge radius and the region of interest was approximated by the flow past an infinite parabolic cylinder. Solutions were obtained by a high-order overset method so that roughness elemental shapes could be accurately represented. The configuration and flow conditions corresponded to an experimental flight test.

An investigation of grid fineness indicated adequacy of the mesh resolution for the baseline flow without roughness. Direct numerical simulations were performed for three different roughness element shapes: cylindrical, square, and a smooth parabolic bump. For cylindrical elements, three different heights were considered. DNS provided detailed solutions of discrete spanwise periodic roughness elements near the leading edge, and were able to capture the generation of crossflow vortices. Characteristics of the perturbation kinetic energy produced by the vortices were elucidated. Disturbances arising from the roughness elements, then served as input to a stability analysis, which was carried out by solution of the nonlinear parabolized stability equations. Two different stability approaches were considered in the investigation. The mean flow could be supplied by the present DNS for flow about a parabolic leading edge without roughness (DNS/NPSE), or could be obtained from a previous Navier-Stokes calculation about the complete experimental aircraft configuration (SWIFT/NPSE).

Initial spatial spanwise frequency spectra indicated the presence of multiple modes, whose contribution was dependent on the element shape. The initial evolution of disturbances could be obtained directly from the DNS roughness solutions, or from the stability analyses. The DNS and DNS/NPSE produced nearly identical results for initial development of the disturbances. Because of the amplitude ratio involved in the definition of the N factor, its initial evolution was insensitive to elemental height in describing growth of the crossflow instability. The initial growth of the velocity amplitude displayed a nonlinear dependence on elemental height, indicating the necessity for performing a DNS for each roughness configuration in order to obtain meaningful perturbation quantities, which may then be utilized to carry out stability calculations. Nonlinear growth rates of the disturbances emphasized the importance of using the NPSE, as opposed to less sophisticated linear methods. The predicted downstream evolution of disturbances seems to correlate reasonably well with the experimentally observed features of transition.

It is believed that the stability approach described here has coupled several key methodologies for investigating receptivity and the evolution of crossflow vortices. The technique provides a framework for relating micron sized roughness elements with the transition location on a swept wing at realistic flight Reynolds numbers. This procedure will also be useful in studying the application of sub critically spaced roughness for laminar flow control, and the effects of natural surface conditions.

SECTION 5

Receptivity, Growth and Secondary Instabilities of Realizable Transient Disturbances

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Abstract

The development of transient growth theory over the past two decades has significantly expanded the scope of traditional stability theory. It provides a framework for understanding the effects of surface roughness and freestream turbulence in contexts that previously would have been labeled "bypass transition" and does so within the context of the familiar Orr–Sommerfeld equation. Much of the theoretical and numerical work on transient growth has concerned "optimal disturbances," those that undergo maximum kinetic energy growth over a specified time or distance. However, experimental work by White and coworkers established that, at least for roughness-induced disturbances, optimal disturbances are not realizable. Some other framework is required to correctly model transiently growing roughness-induced disturbances.

The work reported here considers two critical steps in that modeling effort: receptivity and secondary instabilities. The two phenomena are considered as two separate parts of this report. First is receptivity. Receptivity concerns what distribution of damped eigenmodes is excited by roughness. Second, secondary instability analysis concerns how and where the resulting disturbances break down to turbulence. Between initiation and breakdown, the Orr–Sommerfeld equation correctly models the transient growth. First, the results show that roughness-induced disturbances do indeed produce eigenmode distributions that cannot be model using either optimal-disturbance theory or a linear- receptivity framework. At present, DNS or experiments remain the only tools to calculate transient disturbance receptivity. Second, the results show that even though optimal disturbances have been considered a "worst-case" with regards to the onset of turbulence, they are actually much more stable to secondary instabilities than are non-optimal roughness induced disturbances. Thus, the effort to model non-optimal disturbances is required for even conservative predictions of transition onset.